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SINGLE LEPTOQUARK PRODUCTION*

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ABSTRACT

The single production of leptoquarks in e^+e^-, $e\gamma$ and $\gamma\gamma$ linear colliders is discussed. We show that these new particles could be seen in such machines even if their mass is close to the kinematic limit.

Leptoquarks are predicted in many extensions of the standard model. Although there is no compelling argument that, if they exist, their mass will be low enough that they could be produced in the next generation of colliders, the existence of leptoquarks would be such a striking breakthrough in the search for the physics beyond the standard model that it is important to look for them. Linear colliders would offer a clean environment to do so. The obvious mode to produce leptoquarks is via pair production. While this mode is very interesting and has sizeable cross-sections, it has the drawback that only leptoquarks of masses up to half the center-of-mass energy can be probed. Such leptoquarks will soon be severely constrained by HERA.[1] On the other hand, the single production mechanism allows one to probe twice as large a mass range.

In order to avoid any theoretical bias we will consider all possible leptoquarks and classify them according to their $SU(3)\times SU(2)\times U(1)$ quantum numbers. The most general model-independent Lagrangian[2] that describes the coupling of scalar leptoquarks to fermions can be written as

$$\begin{aligned}\mathcal{L} = \; & g_{1L}\,\overline{q^c_L} i\tau_2 l_L\, S_1 + g_{3L}\,\overline{q^c_L} i\tau_2\tau^i l_L\, S_3^i + h_{2R}\,\overline{q}_L i\tau_2 e_R\, R_2' \; + \; g_{1R}\,\overline{u^c_R} e_R\, S_1' \\ & + \tilde{g}_{1R}\,\overline{d^c_R} e_R\, \tilde{S}_1 + h_{2R}\,\overline{u}_R l_L\, R_2 + \tilde{h}_{2R}\,\overline{d}_R l_L\, \tilde{R}_2 \; . \qquad (1)\end{aligned}$$

Eight different types of interactions of leptoquarks and fermions are described here, namely the right- and left-handed couplings to either $eu, ed, e\bar{d}$ or $e\bar{u}$ (the neutrino couplings are irrelevant), which could make a general analysis of single production rather messy. However, the situation is simpler than it appears since the unpolarized

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Fig. 1. Diagrams giving the dominant contribution to $e^+e^- \to Se^+q$

cross-sections for the processes we will study are the same for both right- and left-handed leptoquarks. Basically there will be only four types of leptoquarks to consider, those of charge $Q_S = -1/3, -2/3, -4/3$ or $-5/3$. In the event that leptoquarks were found, by using polarization it would be a simple task to distinguish the right- and left-handed couplings. Besides the charge and the mass of the leptoquark, the other free parameter is the strength of the coupling, defined as $k = g^2/(4\pi\alpha_{em})$ where g can be any of the coupling constants defined in Eq. 1. We will refer to $k = 1$ as a coupling of electromagnetic strength.

The possibility of leptoquarks coupling to different generations should not be ignored. Here we will assume generation-diagonal leptoquarks since non-generation diagonal ones tend to induce rare decays and are more strongly constrained, typically to the multi-TeV scale.[3] We will also assume chiral leptoquarks, which are less severely constrained than non-chiral ones – the limits are around $M_S/g > 300$ GeV (10 TeV) for chiral (non-chiral) couplings.[4] While fully realizing that these constraints are model dependent and could be evaded, we make these assumptions to emphasize the role of a linear collider in searching for leptoquarks. The important point is that there is still a lot of room for linear colliders to improve on the limits from both indirect and direct searches. This is particularly true for the single production mechanism which probes the region inaccessible to direct searches at HERA.* The present limit from this collider is $M_S > 100 - 200$ GeV for couplings of electromagnetic strength.[1]

First consider the single production of leptoquarks in the process $e^+e^- \to Se^+q$. A large number of diagrams contribute to this process. However, a quick inspection allows for the selection of the dominant diagrams, namely those in which the amplitude diverges in the forward or backward direction. These singularities are regulated by the mass of the lepton or quark involved, giving rise to logarithmic enhancements of the cross section by factors of $\log(s/m^2)$, hereafter called 'large logs'. In Fig. 1, only the dominant diagrams are shown – the first two contain one large log while the last contains two such large logs. Since the dominant term for the cross section is proportional to $(Q_S + 1)^2$, we therefore expect $\sigma_{Q_S=-1/3} \approx \sigma_{Q_S=-5/3} \approx 4\sigma_{Q_S=-4/3} \approx 4\sigma_{Q_S=-2/3}$. This is confirmed numerically[6] as shown in Fig. 2. Note that for this process the forward divergence can be alternatively regulated with a p_T cut (as was done in the first calculation of this process[7]). The advantage of using a mass regulator is that a much larger fraction of the events are kept. In Table 1 we give the results for discovery limits for leptoquarks with couplings of electromagnetic strength for a 500 GeV and

*By indirect searches HERA will be able to significantly improve on those limits.[5]

Fig. 2. Cross-sections for single leptoquark production in e^+e^- at (a) $\sqrt{s} = 500$ GeV (b) $\sqrt{s} = 1$ TeV for the four different leptoquark charges and $k = 1$

1 TeV collider.[6] The criterion for discovery was fixed at 25 events. We can conclude that leptoquarks can be discovered up to essentially the kinematic limit. There is also the possibility of searching for second or third generation leptoquarks through the non-dominant diagrams with s-channel γ/Z exchange. Unfortunately, the cross-section from these diagrams is just too small ($\sigma \approx 10^{-3} fb$).

The three diagrams that contribute to $e\gamma \to qS$ are those shown in Fig. 1 for the e^+e^- process. The only difference is that the photon is obtained by back-scattering laser light off the lepton beam. Again the last diagram gives the dominant contribution due to the large log coming from the collinear singularity in the t-channel regulated by the mass of the quark. The numerical results are given in Ref. 8, and the conclusion is that leptoquarks will be observable up to the kinematic limit for $k = 1$. More weakly coupled leptoquarks are also observable. For example, with the requirement of 25 events and a luminosity of $10 fb^{-1}$ at $\sqrt{s} = 500$ GeV, leptoquarks of $M_S = 400$ GeV are detectable for $k \approx 0.01, 0.02, 0.03$ and 0.08 for $Q_S = -5/3, -1/3, -4/3$ and $-2/3$ respectively. Even heavier leptoquarks would be observable if we consider the virtual production of a leptoquark. In this case, however, we face an important standard model background from $e\gamma \to eq\bar{q}$.

Fig. 3. Diagram giving the dominant contribution to $\gamma\gamma \to Se\bar{q}$

TABLE 1. Maximum leptoquark mass observable in single production.

Process	Q_S	$(M_S)_{max}$ (GeV) $\sqrt{s} = 500$ GeV $\mathcal{L} = 10 fb^{-1}$	$(M_S)_{max}$ (GeV) $\sqrt{s} = 1$ TeV $\mathcal{L} = 60 fb^{-1}$
$e^+e^- \to e^+qS$	$-1/3,\ -5/3$	475	960
	$-2/3,\ -4/3$	420	870
$\gamma\gamma \to e^+qS$	$-1/3,\ -5/3$	480	970
	$-2/3,\ -4/3$	425	920

For the process $\gamma\gamma \to e^+qS$, there are twelve diagrams that contribute. With the same method of looking for large logs it is not hard to convince oneself that only two dominate, the lepton-quark fusion diagram of Fig. 3, and its partner under symmetrization of the photons. Such diagrams will contain two large logs. In Table 1 we give the results for the upper limit of observability of leptoquarks again using the criterion of 25 events.[6] We see that in this process also, leptoquarks of electromagnetic strength can be observed almost up to the kinematic limit. An important point to remember, however, is that in a $\gamma\gamma$ collider, one will not be able to achieve the same center of mass energy as the parent e^+e^- collider since the back-scattered photons obtained from shooting a laser at the lepton beam would have a certain energy spread. Typically we expect to have at most 80% of the energy of the comparable electron machine.

An important feature of the $\gamma\gamma$ process is that one can produce in the same way all generations of leptoquarks, opening up the possibility of producing leptoquarks that couple mainly to second and third generation fermions. One expects, however, that the large logs will not be as important for heavier fermions. By a simple estimate of the ratio of the logarithmic factors involved, we expect the second generation leptoquark production cross-section to be suppressed by a factor 2 or 3 relative to first generation leptoquarks, while that of a τb leptoquark should be suppressed by a factor of 7, and that of a τt leptoquark by a factor of 25 for $m_t = 150$ GeV. The numerical calculation of the cross-sections confirms these naive estimates and full details and the corresponding graphs are given in Ref. 6.

In conclusion, leptoquarks which couple mainly to the first generation can be singly produced in $e^+e^-, e\gamma$ or $\gamma\gamma$ collisions almost up to the kinematic limit if their coupling is of electromagnetic strength. Even much more weakly coupled leptoquarks can be observable, especially in the $e\gamma$ mode. For all processes the largest cross-sections correspond to leptoquarks of charge $-5/3$ and $-1/3$. Finally, in $\gamma\gamma$ collisions there is the possibility of singly producing second and third generation leptoquarks although there are suppression factors relative to the first generation.

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